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# HOW MANY RADIO-LOUD QUASARS CAN BE DETECTED BY THE *GAMMA-RAY LARGE AREA SPACE TELESCOPE*?

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## ABSTRACT

In the unification scheme, radio quasars and FR II radio galaxies come from the same parent population, but viewed at different angles. Based on the Comptonization models for the $\gamma$-ray emission from active galactic nuclei (AGNs), we estimate the number of radio quasars and FR II radio galaxies to be detected by the *Gamma-Ray Large Area Space Telescope* (GLAST) using the luminosity function (LF) of their parent population derived from the flat-spectrum radio quasar (FSRQ) LF. We find that $\sim 1200$ radio quasars will be detected by GLAST, if the soft seed photons for Comptonization come from the regions outside the jets. We also consider the synchrotron self-Comptonization (SSC) model, and find it unlikely to be responsible for $\gamma$-ray emission from radio quasars. We find that no FR II radio galaxies will be detected by GLAST. Our results show that most radio AGNs to be detected by GLAST will be FSRQs ($\sim$99% for the external Comptonization model, EC model), while the remainder ($\sim$1%) will be steep-spectrum radio quasars (SSRQs). This implies that FSRQs will still be good candidates for identifying $\gamma$-ray AGNs even for the GLAST sources. The contribution of all radio quasars and FR II radio galaxies to the extragalactic $\gamma$-ray background (EGRB) is calculated, which accounts for $\sim$30% of the EGRB.

*Subject headings:* galaxies: active—galaxies: jets—accretion, accretion disks—radio continuum: galaxies

## 1. INTRODUCTION

The third catalog of $\gamma$-ray AGNs detected by the Energetic Gamma-Ray Experiment Telescope (EGRET) on the *Compton Gamma-Ray Observatory (CGRO)* includes $\sim 80$ high-confidence identifications of blazars (e.g., Hartman et al. 1999; Mattox et al. 2001). GLAST has higher sensitivity than EGRET, and much more blazars are expected to be detected after its launch. Many workers have predicted the statistic properties of blazars in the GLAST era (e.g., Stecker 1999; Padovani 2007; Dermer 2007). One method is to extrapolate the observed $\gamma$-ray luminosity distribution of EGRET blazars to obtain a $\gamma$-ray luminosity function (LF) (Chiang et al. 1995). An alternative method is to assume some correlation between $\gamma$-ray emission and the emission in other bands to model the undetected $\gamma$-ray blazars, in which the larger samples in other bands provide useful clues to such researches (e.g., Padovani et al. 1993; Stecker et al. 1993; Dermer 2007; Padovani 2007). The previous works on the EGRB showed that about $\sim 25\%$ to $\sim 100\%$ of the EGRB can be attributed to the unresolved blazars (e.g., Padovani et al. 1993; Chiang et al. 1995; Stecker & Salamon 1996; Mücke & Pohl 2000; Narumoto & Totani 2006).

Comptonization is widely believed to be responsible for the $\gamma$-ray emission from the blazars detected by EGRET, which can be classified into two categories: the EC models and SSC model, according to the origin of the soft seed photons (see e.g., Böttcher 2007, for a review and references therein). The space density and evolution of the parent population of blazars, together with the Lorentz factor distribution of the jets, are crucial for understanding the properties of $\gamma$-ray emitting blazars. In almost all previous works, the models of blazars are rather simplified. In this *Letter*, we derive the parent radio LF of radio quasars/FR IIs from the FSRQ LF to investigate the statistic properties of $\gamma$-ray emitting quasars to be detected by GLAST. The cosmological parameters $\Omega_{\rm M}=0.3$, $\Omega_\Lambda=0.7$, and $H_0=70$ km s$^{-1}$ Mpc$^{-1}$ have been adopted in this *Letter*.

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## 2. EC AND SSC MODELS FOR $\gamma$-RAY AGNS

In the EC models, the observed $\gamma$-ray emission from the relativistic jet is closely related to its observed radio emission (see Eq. 26 in Dermer et al. 1997),

$$\nu L_{\nu,\gamma}^{\rm EC}\simeq\frac{3u_{\rm i}^*}{4(p+3)u_{\rm H}}\frac{(1+\mu_{\rm obs})^{(p+3)/2}}{\mu_{\rm obs}}\delta_{\rm j}^{(p+1)/2}\nu L_{\nu,{\rm j}}^{\rm rad}, \qquad (1)$$

where $u_{\rm i}^*$ is the soft seed photon energy density measured in the stationary source frame, $u_{\rm H}$ is the magnetic energy density in the jet, $\mu_{\rm obs}=\cos\theta_{\rm obs}$ ($\theta_{\rm obs}$ is the direction of the jet motion with respect to the line of sight), $\delta_{\rm j}=[\gamma_{\rm j}(1-\beta_{\rm j}\mu_{\rm obs})]^{-1}$ for a jet moving at $\beta_{\rm j}c$, and $\nu L_{\nu,{\rm j}}^{\rm rad}$ is the observed radio luminosity of the jet. The energy distribution of the nonthermal electrons in the jet is assumed to be $n_{\rm e}\propto\gamma_{\rm e}^{-p}$.

In the EC models, the soft photons may originate from the accretion disks, the broad-line regions (BLRs), or/and the dust tori (e.g., Ghisellini & Madau 1996; Georganopoulos et al. 2001; Dermer & Schlickeiser 2002). It was argued that the contribution from the accretion disks is not important, because the $\gamma$-ray emitting region is far away from the disk and in the jet comoving frame, the energy density of photons from the disk is deboosted by the relativistic jet moving away from the black hole (e.g., Sikora et al. 1994; Dermer et al. 1997). It is well known that the BLR size $R_{\rm BLR}\propto L_{\rm bol}^{\alpha_{\rm BLR}}$, where $\alpha_{\rm BLR}\simeq 0.5-0.7$ (e.g., Kaspi et al. 2000; Bentz et al. 2006). Bentz et al. (2006) found that $\alpha_{\rm BLR}$ is 0.518 subtracting the contribution from the host galaxy starlight to $L_{\rm bol}$, which is consistent with $\alpha_{\rm BLR}\simeq 0.5$ expected from the photoionization model if all BLRs have similar physical properties. The inner radius of the dust torus is roughly at the dust evaporation radius: $R_{\rm inn}\propto L_{\rm bol}^{0.5}$ (Netzer & Laor 1993). The photon energy density $u_{\rm i}^*\propto L/R^2$, where $L=L_{\rm BLR}$ and $R=R_{\rm BLR}$ for the BLR photons, and $L=L_{\rm IR}$ and $R\sim R_{\rm inn}$ for the dust torus case. The irradiated infrared luminosity of the dust torus

$L_{\rm IR}\propto L_{\rm bol}$, if the opening angle of the torus does not vary much for individual sources (e.g., Cao 2005). Thus, the energy density of the soft photons from the BLRs/dust tori is roughly universal for most sources. We rewrite Eq. (1) as

$$\nu L_{\nu,\gamma}^{\rm EC}=\mathcal{C}_{\rm EC}\frac{(1+\mu_{\rm obs})^{(p+3)/2}}{\mu_{\rm obs}}\delta_{\rm j}^{(p+1)/2}\nu L_{\nu,\rm j}^{\rm rad}, \quad (2)$$

where the normalization $\mathcal{C}_{\rm EC}$ is related with $u_{\rm i}^{*}/u_{\rm H}$ (see Eq. 1). For the SSC model, the observed $\gamma$-ray luminosity is (see Eq. 28 in Dermer et al. 1997)

$$\nu L_{\nu,\gamma}^{\rm SSC}=\mathcal{C}_{\rm SSC}\nu L_{\nu,\rm j}^{\rm rad}, \quad (3)$$

where $\mathcal{C}_{\rm SSC}$ is the normalization.

## 3. THE PARENT LF OF FSRQS

In the unification scheme, FRSQs, SSRQs, and FR II galaxies come from the same parent population, but viewed at different angles. Some previous authors have derived the parent LF using different approaches (see Cara & Lister 2007; Liu & Zhang 2007), however, they have not compared the number density of blazars with that of radio galaxies.

Padovani & Urry (1992) derived the radio LFs of FSRQs and FR II galaxies from a sample of radio-loud AGNs. They considered a two-component model, in which the total luminosity $L_{\nu,\rm T}$ is the sum of an unbeamed part $\mathcal{L}_{\nu,\rm u}$ and a jet luminosity

$$L_{\nu,\rm j}=\delta_{\rm j}^{3+\alpha_{\rm rad}}\mathcal{L}_{\nu,\rm j}. \quad (4)$$

They used a variety of observational features to constrain the ratio $f(\equiv\mathcal{L}_{\nu,\rm j}/\mathcal{L}_{\nu,\rm u})$. They found that a constant $f\simeq 4.5\times10^{-3}$ can successfully explain the observations (see Padovani & Urry 1992, for the details). Thus, FSRQs should satisfy $\delta_{\rm j}>\delta_{\rm j,min}\simeq 6.45$, as their core dominance parameters $R=L_{\nu,\rm j}/\mathcal{L}_{\nu,\rm u}\gtrsim 1$ is required, where an average core spectral index $\alpha_{\rm rad}=-0.1$ is adopted. They further assumed that the probability distribution of the Lorentz factors for the jets is $P(\gamma_{\rm j})=C\gamma_{\rm j}^{G}$, between $\gamma_{\rm j,1}=5$ and $\gamma_{\rm j,2}=40$. Their derived FSRQ LF is consistent with the beaming model and the LF of FR II galaxies, provided $G=-2.3$ is adopted. Recently, Padovani et al. (2007) derived a FSRQ LF based on the deep X-ray radio blazar survey (DXRBS) in the same way, which extends to lower luminosity than that derived by Padovani & Urry (1992).

The sources in the parent population may be observed as FR IIs, when their jets are oriented at angles $\theta_{\rm obs}\gtrsim 40^\circ$ to the line of sight (e.g., Padovani & Urry 1992). The sources in this parent population with $\theta_{\rm obs}\lesssim 40^\circ$ and $\delta_{\rm j}<\delta_{\rm j,min}$ will appear as SSRQs. The LFs of FSRQs, SSRQs, or FR II galaxies can be reproduced with this parent radio LF, if the probability distribution of the Lorentz factors $P(\gamma_{\rm j})$ is supplied. The LF of FSRQs $\phi_{\rm FSRQ}(L_{\nu,\rm j})$ can be derived from the LF of the parent population $\phi(\mathcal{L}_{\nu,\rm j})$ by

$$\phi_{\rm FSRQ}(L_{\nu,\rm j},z)=\int_{\gamma_{\rm j,1}}^{\gamma_{\rm j,2}}P(\gamma_{\rm j}){\rm d}\gamma_{\rm j}\int_{\mu_{\rm obs}^{\rm min}(\gamma_{\rm j})}^{1}\phi(\mathcal{L}_{\nu,\rm j},z)\frac{{\rm d}\mathcal{L}_{\nu,\rm j}}{{\rm d}L_{\nu,\rm j}}{\rm d}\mu_{\rm obs}, \quad (5)$$

where the orientations of the jets of the parent population are assumed to be isotropically distributed, and only those with $\mu_{\rm obs}\geq\mu_{\rm obs}^{\rm min}(\gamma_{\rm j})=(\gamma_{\rm j}\delta_{\rm j,min}-1)/(\gamma_{\rm j}^2-1)^{1/2}\delta_{\rm j,min}$ are FSRQs, which is required by FSRQs having $R\gtrsim 1$. Equation (5) can be re-written as

$$\phi_{\rm FSRQ}(L_{\nu,\rm j}^{i},z)=\sum_{k=1}^{n}\phi(\mathcal{L}_{\nu,\rm j}^{k},z)\epsilon_{ik}, \quad (6)$$

where $i=1,n$, and

$$\epsilon_{ik}=\int_{\gamma_{\rm j,1}}^{\gamma_{\rm j,2}}P(\gamma_{\rm j}){\rm d}\gamma_{\rm j}\int_{\mu_{\rm obs}(\gamma_{\rm j})}\left.\frac{{\rm d}\mathcal{L}_{\nu,\rm j}}{{\rm d}L_{\nu,\rm j}}\right|_{L_{\nu,\rm j}=L_{\nu,\rm j}^{i}}{\rm d}\mu_{\rm obs}. \quad (7)$$

The coefficient $\epsilon_{ik}$ can be calculated with Eq. (7) by using Eq. (4) and adopting the integral limits $\mu_{\rm obs}(\gamma_{\rm j})$ to satisfy $\mathcal{L}_{\nu,\rm j}^{k}-\Delta\mathcal{L}_{\nu,\rm j}/2\leq\mathcal{L}_{\nu,\rm j}\leq\mathcal{L}_{\nu,\rm j}^{k}+\Delta\mathcal{L}_{\nu,\rm j}/2$. Solving a set of $n$ linear algebraic equations (6) numerically, the parent LF $\phi(\mathcal{L}_{\nu,\rm j},z)$ can be calculated from the LF of FSRQs $\phi_{\rm FSRQ}(L_{\nu,\rm j},z)$ given by Padovani et al. (2007).

## 4. NUMBER OF GLAST QUASARS

Using this derived parent radio LF, we can calculate the observed $\gamma$-ray LF $\phi_\gamma$ for FSRQs, SSRQs and FR II galaxies based on either EC or SSC models:

$$\phi_\gamma^{\rm EC/SSC}(L_{\nu,\gamma}^{\rm EC/SSC},z)=\int_{\gamma_{\rm j,1}}^{\gamma_{\rm j,2}}P(\gamma_{\rm j}){\rm d}\gamma_{\rm j}\int_{\mu_{\rm obs}(\gamma_{\rm j})}\phi(\mathcal{L}_{\nu,\rm j},z)\frac{{\rm d}\mathcal{L}_{\nu,\rm j}}{{\rm d}L_{\nu,\gamma}^{\rm EC/SSC}}{\rm d}\mu_{\rm obs}, \quad (8)$$

where ${\rm d}\mathcal{L}_{\nu,\rm j}/{\rm d}L_{\nu,\gamma}^{\rm EC/SSC}$ can be derived from Eqs. (2)–(4). This $\gamma$-ray LF is not limited to blazars, as their parent radio LF is adopted in the calculations. Adopting the conditions for different sources (i.e., $\delta_{\rm j}>\delta_{\rm j,min}$ for FSRQs; $\theta_{\rm obs}\gtrsim 40^\circ$ for FR II galaxies; and the remainder are SSRQs), the numbers of the FSRQs/SSRQs/FR II galaxies with $f_{\nu,\gamma}\geq f_{\nu,\gamma}^{\rm min}$ as functions of redshift $z$ can be calculated by

$$\frac{{\rm d}N^{\rm EC/SSC}(z)}{{\rm d}z}=\int_{4\pi d_{\rm L}^2 f_{\nu,\gamma}^{\rm min}}\frac{{\rm d}V}{{\rm d}z}\phi_\gamma^{\rm EC/SSC}(L_{\nu,\gamma}^{\rm EC/SSC},z){\rm d}L_{\nu,\gamma}^{\rm EC/SSC}, \quad (9)$$

either for EC or SSC models, respectively.

Sixty three $\gamma$-ray emitters were identified as blazars at high confidence with measured redshifts in Hartman et al. (1999). More $\gamma$-ray sources were identified as blazars afterwards (Mattox et al. 2001; Sowards-Emmerd et al. 2003, 2004; Sguera et al. 2004). We collect all these $\gamma$-ray blazars identified at high confidence, which leads to 64 quasars and 16 BL Lac objects with measured redshifts. We note that the measured fluxes with photon energy greater than 100 MeV $\gtrsim 5\times10^{-8}$ photons cm$^{-2}$ for all EGRET blazars. This can be translated to $\nu f_{\nu,\rm EGRET}^{\rm min}\simeq 8\times10^{-12}$ erg s$^{-1}$ cm$^{-2}$ at 100 MeV assuming a mean photon spectral index of 2 (Hartman et al. 1999), which corresponds to $p=3$ (Dermer et al. 1997).

We calculate the number counts of $\gamma$-ray quasars with $\gamma$-ray flux densities greater than $f_\nu^{\rm min}$ at 100 MeV using Eq. (9), based on the different $\gamma$-ray radiative models (EC or SSC models). We tune the values of the parameters $\mathcal{C}_{\rm EC}$ or $\mathcal{C}_{\rm SSC}$ to let the total number of FSRQs derived with Eq. (9) equal to that of the FSRQs detected by EGRET. We find that $\mathcal{C}_{\rm EC}=4.42\times10^{-3}$ or $\mathcal{C}_{\rm SSC}=10.62$ are required to reproduce 64 FSRQs detected by EGRET for the EC or SSC models, respectively. Based on the derived values of $\mathcal{C}_{\rm EC}$ or $\mathcal{C}_{\rm SSC}$, the number counts of $\gamma$-ray emitting quasars/FR IIs to be detected by GLAST can be predicted by adopting different flux density limits $f_{\nu,\rm min}$ with Eq. (9) (see Fig. 1 and Table 1).

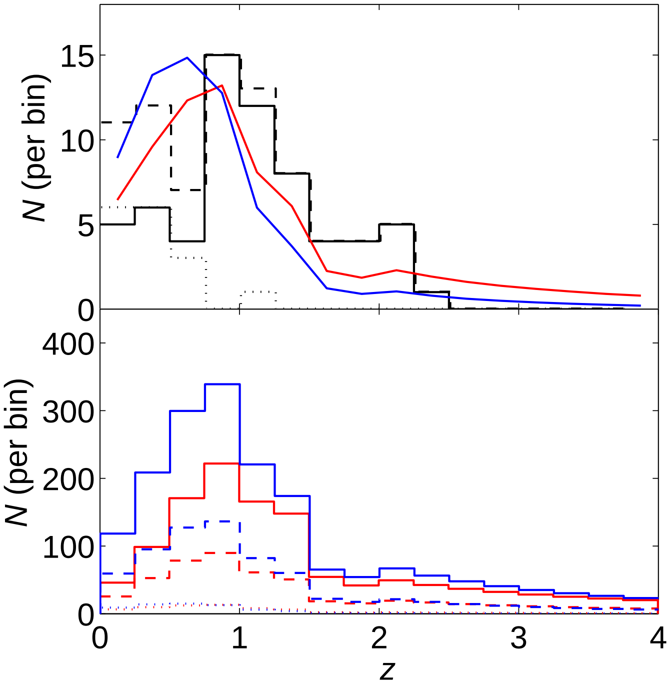


FIG. 1.— Upper panel: the redshift distributions of the EGRET blazars (the black solid line: quasars; the dashed line: all EGRET blazars; the dotted line: BL Lac objects). The color lines represent our model calculations for 64 quasars. The red line represents the model prediction based on the EC model, while the blue line represents the result for SSC model. Lower panel: the calculated redshift distributions of $\gamma$-ray quasars detected with different flux density limits. The red lines represent the calculations based on the EC model, while the blue lines are for the SSC model. The dotted lines represent our model calculations for EGRET quasars. The dashed lines represent the redshift distribution of the $\gamma$-ray quasars with $\geq 0.1 f_{\rm limit}^{\rm EGRET}$ at 100 MeV, while the solid lines are for the sources with $\geq 1/30 f_{\rm limit}^{\rm EGRET}$.

The total numbers of $\gamma$-ray emitting radio quasars/FR IIs as functions of sensitivity are plotted in Fig. 2. About 1200 $\gamma$-ray radio quasars will be detected by GLAST based on the EC model, if its sensitivity is 30 times higher than that of EGRET at 100 MeV (Gehrels & Michelson 1999). Our calculations show that no FR II radio galaxies will be detected by GLAST as $\gamma$-ray emitters either for EC or SSC models. We find that almost all $\gamma$-ray quasars ($\sim$99%) to be detected by GLAST will be FSRQs for the EC model, and the remainder ($\sim$1%) will be SSRQs. For the SSC model, $\sim$ 1800 quasars will be detected by GLAST, of which $\sim$80% will be FSRQs (see Fig. 2). We use the derived $\gamma$-ray LF (Eq. 8) to calculate the contribution of all radio quasars/FR IIs to the EGRB (listed in Table 1).

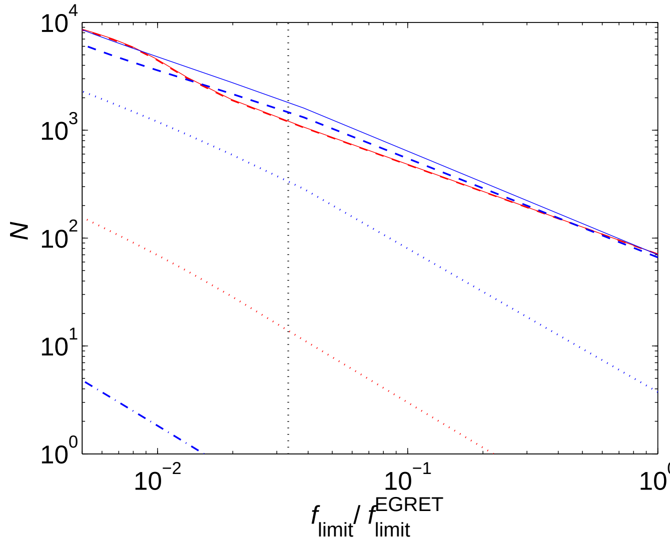


FIG. 2.— The total number of the $\gamma$-ray quasars with flux densities greater than $f_{\rm limit}$ at 100 MeV. The red lines are calculated for the EC model, while the blue lines are for the SSC model. The dashed lines represent the $\gamma$-ray FSRQs, while the colored dotted lines represent the $\gamma$-ray SSRQs. The dash-dotted line represents the FR II radio galaxies. The black dotted line represents the GLAST sensitivity at 100 MeV.

## 5. DISCUSSION

We find that the redshifts of almost all EGRET BL Lac objects are $\lesssim 1$, which implies that BL Lac objects may have different space density and evolutionary behaviors from quasars. The LF of BL Lac objects was derived from the DXRBS by Padovani et al. (2007), however, the results for BL Lac objects are more uncertain than those for FSRQs, because of the small number statistics and $\sim$30% of them having no redshift. In this work, we use a parent radio LF of radio quasars/FR II galaxies derived from the FSRQ LF. The derived redshift distributions of $\gamma$-ray quasars are similar for different models (EC or SSC), which are roughly consistent with that of the EGRET quasars.

It was suggested that the $\gamma$-ray radiative mechanisms are different for quasars and BL Lac objects, i.e., the EC mechanism may be responsible for quasars, while the SSC is for BL Lac objects (e.g., Dondi & Ghisellini 1995). If the EC mechanism is indeed responsible for $\gamma$-ray quasars, the predicted $\gamma$-ray quasars to be detected by GLAST will be $\sim$ 1200. Our results are roughly consistent with the estimate given by Dermer (2007) based on a simplified blazar model. The SSC model predicts a simple relation between $\gamma$-ray luminosity and radio luminosity of the jets (see Eq. 3). The EGRET flux limit $\nu f_{\nu,\rm EGRET}^{\rm min}$ at 100 MeV can be converted to a radio flux density limit $f_{\nu,\rm rad} \sim 10$ Jy at 5GHz by using Eq. (3). This means that all EGRET quasars should have their radio flux densities higher than $\sim$ 10 Jy, which is obviously inconsistent with most EGRET quasars having $f_{\nu,\rm rad} \gtrsim 1$ Jy (e.g., Stecker et al. 1993; Zhou et al. 1997). Thus, the SSC model is unlikely to be responsible for EGRET quasars, unless the physical properties of the jets are significantly different for individual sources, i.e., the values of $\mathcal{C}_{\rm SSC}$ for most sources deviate significantly from a constant value.

Our results show that no FR II galaxies will be detected by GLAST. Most GLAST quasars will be FSRQs ($\sim$99% for the EC model), which implies that FSRQs will still be good candidates for identifying the $\gamma$-ray sources even for the GLAST

TABLE 1
THE SUMMARY OF DIFFERENT MODELS

| $\mathcal{C}_{\rm EC}$ | $\mathcal{C}_{\rm SSC}$ | N($\geq \nu f_{\nu,\rm limit}^{\rm EGRET}$)[a] | N($\geq 1/10\nu f_{\nu,\rm limit}^{\rm EGRET}$) | N($\geq 1/30\nu f_{\nu,\rm limit}^{\rm EGRET}$) | $f_{\rm EGRB}$[b] |
|---|---|---|---|---|---|
| $4.42\times10^{-3}$ | ... | 64 | 491 | 1203 | 0.32 |
| ... | 10.62 | 64 | 696 | 1806 | 0.30 |
| ; | | | | | |

[a] The number of FSRQs with $\geq \nu f_{\nu,\rm limit}^{\rm EGRET} \simeq 8\times10^{-12}$ erg s$^{-1}$ cm$^{-2}$ at 100 MeV.[b] for the photons with energy above 100 MeV in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

sources. At least two FR I galaxies have been detected by EGRET (e.g., Padovani 2007), and more FR I galaxies were predicted to be detected by GLAST (e.g., Ghisellini et al. 2005). In the unification scheme, FR I galaxies are BL Lac objects with misaligned jets. The $\gamma$-ray FR I galaxies/BL Lac objects are beyond the scope of this work. The EGRET quasars identified at high confidence (64 sources) have radio flux densities $\gtrsim 1$ Jy and are about 20% of the total FSRQs ($\sim 300$) above the same flux density limit (see Fig. 6 in Padovani et al. 2007). Assuming the radio flux density limit of the GLAST quasars to be $\sim 30$ times lower than the EGRET limit, i.e., $\sim 30$ mJy, the total all-sky number of the FSRQs above this limit is about 20000. So, about 4000 FSRQs will be detected by GLAST, if the same percentage ($\sim 20$%) is adopted as the EGRET blazars. This rough estimate is about a factor of two higher than our model calculations. Considering that some unidentified $\gamma$-ray sources are likely to be blazars, our estimates on $\gamma$-ray quasars to be detected by GLAST are only lower limits. Both the duty cycle in the $\gamma$-ray band and identification rate may affect the detection rate, and we implicitly assume them to be similar to those of EGRET blazars.

The EGRB integrated above 100 MeV was determined to be $1.45(\pm0.05)\times10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ from the EGRET data (Sreekumar et al. 1998). Strong et al. (2004) used a new model of the Galactic background, and obtained a slightly smaller value of the EGRB, $1.14(\pm0.12)\times10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. We sum up the $\gamma$-ray emission from all radio quasars/FR IIs with our derived $\gamma$-ray LF and find that they contribute $\sim$30% of the EGRB (see Table 1), which are only lower limits, because our calculations are limited to radio quasars/FR II galaxies. The BL Lac objects/FR Is must contribute some part to the EGRB. The detailed calculation of their contribution to the EGRB is beyond the scope of this *Letter*.

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